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Economic analysis of heating and cooling systems from the various perspectives: Application to EHP and GHP in Korea

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ABSTRACT

Energy flow from the primary energy to the final energy use varies depending on which device is used for the heating and cooling energy service. This paper presents economic analyses of medium capacity space heating and cooling systems from three perspectives – primary energy, final consumer, and social cost perspective. From the analysis results of primary energy and final consumer perspective, electric heat pump (EHP) system is found to be superior to the gas engine driven heat pump (GHP) system for the energy consumption and cost-effectiveness due to its higher system efficiency. However, the result of social cost perspective shows the GHP system is superior to the EHP system considering incurred incremental electricity generation capacity construction cost and avoided gas storage tank construction cost due to a new installation of each system. And this paper suggests three analysis methodologies – the primary energy, final consumer, and social cost perspective – can be used for developing various measures and policies for integrated demand side management.

Contents

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1. Introduction

While climate change is a major global issue, the global energy consumption is continuously increasing to maintain economic activities. In Korea, the energy consumption has been increased significantly since the start of the industrialization in 1970s and is expected to continuously increase in spite of slowing down population increase and economic growth. In this situation, the efforts to use energy efficiently as well as to save energy are required to reduce CO_2 emission.

During the last 2 years, there are dramatic changes in consumers' choice of energy sources for their heating and cooling. Consumers' increased preference for electricity becomes a problem in national energy resource management. This phenomenon seems natural and foreseeable since electricity price has been relatively low compared with other energy resources for heating and cooling and electric heating and cooling appliances are more convenient for consumers to use than others.

Most electric appliances such as television, refrigerator and washing machine have no choice but to use electricity as their power source. However, cooling and heating appliances are different from them. Various energy and technology options are available for heating and cooling. Consumers may choose their appliance and energy source considering the price of energy, the price of appliances and the convenience of use. In other words, consumers make a choice based on their own view of the each option's cost effectiveness. However, it is not expectable consumers consider the cost effectiveness in national perspective.

An energy source chosen or preferred by consumers may not always be said socially desirable one. Therefore, an analysis of energy use for heating and cooling in social perspective should be made to induce consumers' energy use in the right direction. Recent increased use of electricity evoked by the increased use of electrical heating and cooling system, forces the construction of more power plants than planned. The construction of power plants and transmission lines becomes more and more difficult since public acceptance on these facilities is worsening. Worsening public acceptance also causes the increase of the costs. In addition, the lowered load factor caused by increased use of electrical heating and cooling system will result in the increased electricity supply cost. Thus, it is quite an urgent issue to analyze the costs of heating and cooling systems in national perspective in order to prepare a proper direction of energy use in heating and cooling.

Thus, this paper analyzes the cost of heating and cooling systems fueled by electricity and gas, the major energy sources for heating and cooling service, in the aspect of energy flow ranging from energy supply to consumption.

Recently, a few studies compared heating and cooling systems which use different energy sources. Kim et al. reviewed energy costs and CO_2 emission of electric heat pump (EHP) and gas engine driven heat pump (GHP) from the final consumer perspective and suggested that GHP is advantageous for the amount of energy consumption and energy costs, and EHP is advantageous for CO_2 emission [1]. Kim suggested economic analysis methodology from the final consumer perspective and reported that overall cost of EHP is less than that of GHP [2]. Brenn et al. reported that EHP and GHP are similar in function, but GHP would be better for CO_2 emission [3].

This paper conducts energy flow analysis, considering technical efficiency of each phase, i.e., energy supply, conversion, transmission and distribution, and final consumption. Further, this paper makes a comparative analysis of EHP and GHP from three perspectives, i.e., primary energy perspective, final consumer perspective and social cost perspective. The purpose of this paper is to provide a series of comparative analysis methodologies with various perspectives for national energy policy establishment or consumer's decision making.

This paper proceeds as follows. In Section 2, the recent heating and cooling demand status and necessity of integrated demand side management in Korea are discussed. In Section 3, we established the methodologies for analyses from various perspectives. Section 4 contains a description of our data and reports the results of analysis and sensitivity analysis. Section 5 presents conclusions and some discussion on the results.

2. Status of heating and cooling demand and the integrated demand side management in Korea

This section presents the current status of electricity demand for heating and cooling in Korea. To analyze the heating and cooling energy service, the penetration status of EHP and GHP and technical characteristics of them are reviewed. And necessity of the integrated demand side management for rational energy use is discussed.

2.1. Recent status and prospects of heating and cooling energy demand

Electricity load management programs in Korea have been focusing on the summer peak demand reduction. Summer peak has shown rapid growth with increased cooling demand. However, for the past a few years, winter electricity demand has increased drastically, and in 2009, winter peak demand surpassed the summer peak demand.

Fig. 1 shows the peak demands of summer and winter during the last 10 years. In the winters of 2007 and 2008, the winter peak demands almost reached the summers'. Especially, the winter peak demand of 2009 was 68,655 MW, nearly 5343 MW higher than 63,212 MW of the summer peak demand. According to the outlook from the Korea Power Exchange (KPX) [4], the summer electric cooling load in 2010 is estimated as 15,020 MW, 21.2% of the summer peak demand, and the winter electric heating load is estimated as 16,750 MW, 24.4% of the winter peak demand.

2.2. Penetration status of EHP and GHP systems

Recently, the electricity demand growth caused by winter heating has been higher than that by summer cooling. The reason for this phenomenon is presumed as the energy price structure in Korea. Relatively lower electricity price than other energies, enabled consumers to use electric heating appliances such as electric blankets, electric stoves, home heating appliances, auxiliary heat sources of small building and etc. Especially, the explosive penetration of EHP system, featured as easier management and cheaper appliance price than other systems, for medium-sized buildings such as schools and commercial buildings appears to mainly contribute the recent increase in the winter peak load.

As shown in Table 1, the installation of GHPs has been slowing down while that of EHP increased rapidly [5]. Relatively higher gas rates and inconvenience of GHP causes the continuous declination of GHP's market share.

Recent study on electricity demand prospects of Korea [6], which forecasted the electricity demand would reach 81,805 MW by the year 2022 and the installed reserve margin would be between 6% and 10% until 2011 and between 12% and 24% after 2012, expressed the need for measures to stabilize the short-term supply and demand balance. In this situation, the demand management should focus on not just summer demand management, but whole year. In addition, demand management by the

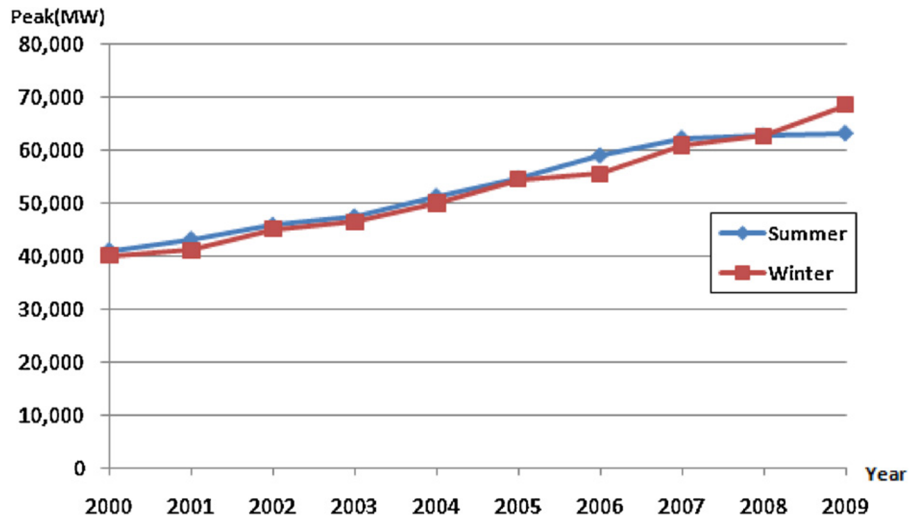


Fig. 1. Recent summer and winter electricity peak.

coordination of energy resources is also required as well as that by the adjustment of electricity use.

2.3. Integrated demand side energy management

Depending on the purpose of consumer's heating and cooling, consumers consider various factors in choosing their heating and cooling devices. Installation costs, energy costs, operating costs, maintenance costs, equipment life, and, etc. could be the factors. From the consumers' point of view, they will try to obtain the maximum benefit at minimum cost.

However, from the national and social point of view, it has quite different characteristics. Electric power is generally delivered to the consumers by converting primary energy – LNG, oil, coal, and, etc. – into electrical energy. Therefore, if electrical heating and cooling consumption continues to increase, power plants have to accept the additional burden. It causes the deterioration of power system reliability and load factor of the power system. As a result, the costs of electricity supply could rise. Especially as the consumption of natural gas in summer is lower than that in winter, if the cooling is made by natural gas, constructions of various facilities such as power plants and natural gas storage can be avoided and this will ultimately reduce the cost of primary energy imports.

If the choices of heating and cooling technologies are reasonably coordinated in social point of view, the energy cost could be saved and the saved costs could be returned to the consumers. At the same time, the national energy supply and demand system would evolve to a desirable direction. In Korea, this kind of government intervention on consumers' energy use or choice of technologies is called 'Integrated Demand Side Management' [7].

3. Analysis methodologies

As previously mentioned, economic values of energy services are different depending on the perspective of analysis. This paper attempts to analyze EHP and GHP, the most commonly adopted heating and cooling system for medium-size buildings, from following three perspectives:

- Primary energy perspective,
- Final consumer perspective,
- Social costs perspective.

Table 1
Penetration status of EHP and GHP in Korea.

Units	2004	2005	2006	2007	2008
EHP	–	37	773	62,733	45,695
GHP	4229	5223	5884	4020	3720

3.1. Primary energy perspective analysis

Energy flow from the primary energy supply to the final energy consumption varies depending on which energy source is used for the heating and cooling service. Fig. 2 shows the energy flow of heating and cooling service from the primary energy to the end-use.

There are energy losses during the conversion and distribution to the final consumption. Therefore, the amount of primary energy required to provide same heating or cooling energy is different depending on which system is adopted. Generally, the main difference between electric energy and gas energy is that electricity needs a generation process to convert primary energy into electric power. Typically only 40% of the primary energy supplied to a generating plant can be provided to final consumers because of energy losses during the generation, transmission, and distribution. From the final energy point of view, whereas electricity using appliances have a high efficiency, the enhancement of efficiency in the generation, transmission and distribution process is critical in improving the overall efficiency of electrical energy service.

Therefore, conversion into the primary energy consumption considering the change of the property or the loss of the primary energy in the energy delivery process is required to compare the primary energy consumption of EHP and GHP.

In case of EHP, the primary energy is supplied to a generator and converted into electricity, and then it is delivered to consumers through transmission and distribution lines. Therefore, the primary energy requirement to use the EHP system can be defined as follows:

$$F_G = \sum_i \frac{E_{EHP}}{COP_{EHP} \times \eta_{E,G,i}(1-\eta_{E,T\&D})860} \times \omega_i \tag{1}$$

where F_G is primary energy requirement for EHP [kcal], E_{EHP} is amount of electricity consumption [kWh], COP_{EHP} is coefficient of performance of EHP, $\eta_{E,G,i}$ is efficiency of generation source type-i [%], $\eta_{E,T\&D}$ is electricity transmission and distribution loss factor [%], ω_i is weight factor of generation source type-i, 860 is conversion factor [kcal/kWh].

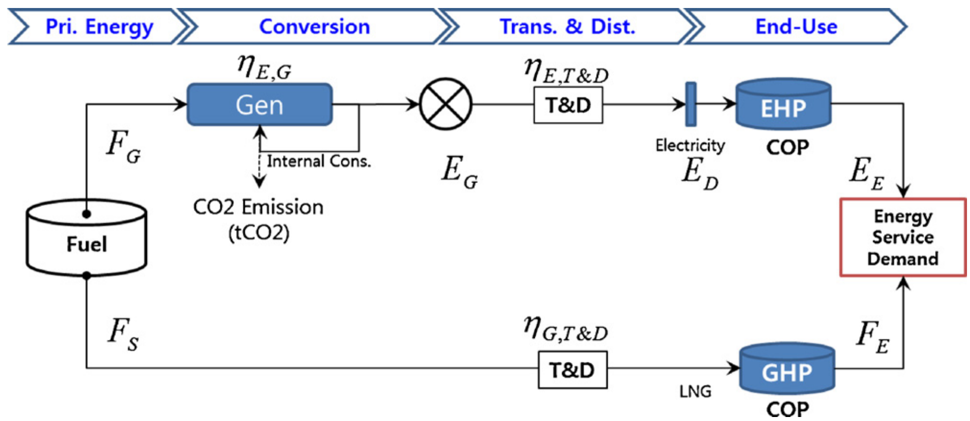


Fig. 2. Energy flow for cooling and heating.

The index used to indicate the performance of EHP and GHP is the COP (coefficient of performance) [8]. The COP, a dimensionless index, denotes the ratio of useful heat output to work input. For converting power consumption of EHP into primary energy, it should be identified which power generation source provides electricity to the EHP system. In order to identify the generation source, this paper adopted "Proxy Plant" approach which determines power plant type similar with load profile or operational characteristic of the end use facility. Under this approach, a fixed hypothetical plant is used as a proxy for the resources that will be built to meet incremental load [9]. Typically, heating and cooling systems such as EHP and GHP affect the commitment of peaking power plant which determines SMP (System Marginal Price) in the electricity market. Therefore, in this paper, we applied weight parameter ω_i based on SMP determination weight of natural gas fired combined cycle generator and oil fired generator in Korea Electricity Market during 8760 h.

In case of GHP system, it consumes natural gas by gas engine and electricity by electric equipment, respectively. Therefore, the primary energy consumption of GHP system can be expressed as the sum of the natural gas used by the gas engine and the primary energy supplied to the power plant in order to supply electricity to the electric equipment of GHP system. Firstly, natural gas consumption is calculated based on the COP of the gas engine and natural gas transmission and distribution loss factor. Secondly, primary energy supplied to the electric equipment of GHP system is calculated in the same way as primary energy requirement calculation of EHP system. Therefore, the primary energy supply to the GHP system can be formulated as follows:

$$F_S = \frac{F_{GHP}}{COP_{GHP}(1-\eta_{G,T\&D})} + \sum_i \frac{E_{Equip}}{\eta_{E,G,i}(1-\eta_{E,T\&D})860} \times \omega_i \qquad (2)$$

where Fs is primary energy requirement for GHP [kcal], F_{GHP} is natural gas consumption by gas engine [kcal], COP_{GHP} is coefficient of performance of GHP, E_{Equip} is electricity consumption by electric equipment of GHP [kWh], $\eta_{G,T\&D}$ is natural gas transmission and distribution loss factor [%], $\eta_{E,G,i}$ is efficiency of generation source type-i [%], $\eta_{E,T\&D}$ is electricity transmission and distribution loss factor [%], ω_i is weight factor of generation source type-i [%], 860 is conversion factor [kcal/kWh].

The LCP is the levelized cost from the primary energy perspective, which means an annual primary energy supply cost to operate EHP or GHP. The LCPs of EHP and GHP are calculated as follows:

$$LCP = \sum_i (F_i \times FP_i) \qquad (3)$$

where F_i is supply of primary energy-i, FP_i: unit price of primary energy-i.

3.2. Final consumer perspective analysis

The analysis from the final consumer perspective starts with calculation of the energy costs of each heating and cooling systems based on the consumer price of electricity and gas. Then, initial investment cost and annual operation and maintenance costs are added to the energy costs so that we can make a comparison between two systems.

The initial investment cost consists of indoor and outdoor equipment purchase cost, electric equipment purchase cost, construction and installation cost, miscellaneous equipment cost, and installation subsidy. The installation subsidy is only for GHP system installation and it is supported by Korea Gas Corporation's 'Gas Cooling System Subsidy Program' which has been implemented for natural gas demand creation during summer season. A consumer who installs GHP system can receive KRW 200,000/RT by this program. And annual operation cost consists of annual maintenance cost including space usage charge, repair charge and insurance premium.

The initial investment costs have to be levelized to get annual cost by considering lifetime of the system and discount rate. The factor to calculate levelized cost is defined as CRF (capital recovery factor), which is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. Using a discount rate i, the CRF is:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (4)$$

where n is the number of annuities received [10].

The following equation is the levelized cost from the final consumer perspective based on the investment cost, annual energy costs and annual operation costs.

$$LCC = CRF \times IC + EC + OM \qquad (5)$$

where LCC is levelized cost from the final consumer perspective, IC is initial investment cost, EC is annual energy cost, OM is annual operation and maintenance cost.

3.3. Social costs perspective analysis

The analysis from the social costs perspective includes additional costs by new installation of the heating and cooling system. The social costs consist of primary energy costs, initial investment and O&M costs of the consumer, incremental electricity generation

capacity construction costs, avoided LNG storage tank construction costs, and environmental costs for greenhouse gas emission in energy conversion and consumption process.

The incremental electricity generation capacity construction cost is defined as the cost required for additional power plant construction that are needed by the increased peak demand following new installation of the electric heating and cooling system. In selecting power generation plant type, "Proxy Plant" approach is applied, which models power plant type similar with load profile or operational characteristic of the end use facilities. Firstly, annuity of the power plant construction costs is calculated by multiplying total power plant construction cost and CRF, and then availability of power plant, internal consumption rate, and T&D loss factor are applied to get incremental electricity generation capacity construction cost. Secondly, levelized unit incremental electricity generation capacity construction cost is calculated by dividing the sum of incremental electricity generation capacity construction costs and annual fixed O&M cost by the capacity of power plant.

Avoided LNG storage tank construction cost is caused by natural gas import contracts structure in Korea. Korean domestic natural gas demand is high in winter and low in summer season, whereas the amount of natural gas import in each month is fixed by long-term contracts. Thus, in the summer season, surplus natural gas should be stored in LNG storage tank. Therefore, if an LNG fueled combined-cycle power plant is selected as a required source for increased summer electricity demand by the EHP or electric equipment of the GHP, natural gas consumption by the power plants will increase and additional LNG storage tank construction could be avoided. Likewise, increased natural gas consumption by gas engine of the GHP system can also contribute to avoiding the additional LNG storage tank construction.

Firstly, an incremental generation capacity construction cost is calculated by multiplying incremental electricity peak demand and levelized unit generation construction cost. The incremental electricity peak demand is defined as the product of full-load power consumption and load factor of cooling or heating device during peak hours.

$$\mathrm{IGC} = \mathrm{ID} \times \mathrm{LC} = \mathrm{PC}_{\text{Full-load}} \times \mathrm{LF}_{\text{Peak}} \times \mathrm{LC} \tag{6}$$

where IGC is incremental generation capacity construction cost [KRW], ID is incremental electricity peak demand [kW], LC is levelized unit generation construction cost [KRW/kW], $\mathrm{PC}_{\text{Full-load}}$ is full-load power consumption of the heating or cooling system [kW], $\mathrm{LF}_{\text{Peak}}$ is load factor of heating or cooling system during peak hours [%].

Secondly, the avoided LNG storage tank construction cost is calculated by Eq. (7), which is defined by the product of the previously defined primary energy consumption in Section 3.1 and unit avoided LNG storage tank construction cost.

$$\mathrm{AGC} = F_{\mathrm{LNG}} \times \mathrm{UAC}_{\mathrm{LNG}} \tag{7}$$

where AGC is avoided LNG storage tank construction cost [KRW], F_{LNG} is natural gas consumed by GHP system [ton], $\mathrm{UAC}_{\mathrm{LNG}}$ is unit avoided LNG storage tank construction cost [KRW/ton].

Thirdly, environmental cost is calculated by Eq. (8), which is defined by the product of unit emission cost and greenhouse gas emissions from primary energy combustion.

$$\mathrm{ENC} = \sum_i (\mathrm{PEC}_i \times \mathrm{EF}_i) \times \mathrm{UEC} \tag{8}$$

where ENC is annual environmental cost, PEC_i is primary energy consumption of source-i [TOE], EF_i is CO_2 emission factor of primary energy source-i [tCO_2/TOE], UEC is unit emission cost [KRW/tCO_2].

Table 2
Input data for calculating demand.

	Unit	Cooling	Heating
Capacity	RT	30	30
Operating hour	h	1000	2000
Conversion factor	kcal/RT	3024	3024
Demand	Mcal	90,720	181,440

Table 3
The economic analysis index.

Factor	Unit	EHP	GHP
Discount rate	%	7.50	7.50
Life expectancy	Years	10	8
CRF	%	14.57	17.07

Finally, a levelized cost from the social cost perspective caused by new installation of the heating and cooling system, based on the costs previously defined, is calculated as follows:

$$\mathrm{LCS} = \mathrm{LCP} + \mathrm{CRF} \times \mathrm{IC} + \mathrm{OM} + \mathrm{IGC} + \mathrm{AGC} + \mathrm{ENC} \tag{9}$$

where LCS is levelized cost from the social cost perspective, LCP is annual primary energy cost, CRF is capital recovery factor of the system, IC is initial investment costs, OM is annual O&M cost, IGC is incremental electricity generation capacity construction costs, AGC is avoided LNG storage tank construction cost, ENC is annual environmental cost.

4. Analysis results

4.1. Assumptions

For the analysis, the total heating and cooling energy demand considering standard heating and cooling equipment capacity and annual operating hour is assumed as in Table 2. The total heating and cooling demand is calculated as follows:

$$D = C \times \mathrm{OH} \times \mathrm{CF} \times 10^{-3} \tag{10}$$

where D is annual heating and cooling demand [Mcal], C is equipment capacity [RT], OH is annual operating hours [h], CF is conversion factor from RT to kcal.

Indices for the economic analysis from each perspective are assumed in Table 3.

Table 4 indicates the typical COPs of EHP and GHP in the 30 RT (Refrigeration ton) class [11]. The COPs of EHP system are more than twice as high as those of GHP system. And COP for heating is even higher than that for cooling.

Generation sources and weight values, show in Table 5, which are used for the analysis from the primary energy perspective, are based on Korea Energy Management Corporation's research results in 2009 [7]. Efficiency of power generation and transmission and

Table 4
Cooling and heating COPs of each system.

	EHP		GHP	
	Cooling	Heating	Cooling	Heating
COP	2.95	3.65	1.26	1.48

Table 5
Input data for each generation sources.

Fuel type	Eff. of Gen.	T&D loss	Weight
LNG (%)	45.47	4.39	75
B–C (%)	35.16	4.39	25

Table 6
Unit supply price of primary energy (kKRW/Gcal).

LNG	Terminal price	44.57
	Supply cost	5.64
	Subtotal	50.20
B–C	Consumer price	48.90

※
kKRW: 1000 KRW.

Table 7
Initial cost of each system (kKRW).

	EHP	GHP
Outdoor equipment	36,000.00	39,440.00
Indoor equipment	9800.00	9800.00
Miscellaneous equipment	320.00	2535.00
Electrical equipment	6504.00	902.40
Installation	8800.00	14,200.00
Construction	400.00	200.00
Financial subsidy	–	−6000.00
Total	61,824.00	61,077.40

distribution loss factors are based on the average values of actual data provided by Korea Power Exchange [12].

The unit prices to supply primary energy are shown in Table 6 [13].

Tables 7 and 8 show the initial investment costs and annual O&M costs of EHP and GHP. The values are same as those in Kim's research [1]. Because the consumer who installs GHP system is supported with KRW 200,000/RT by subsidy program, the consumer who installs the GHP of 30 RT-scale can get KRW 6 million.

4.2. Results by analysis perspective

4.2.1. Primary energy perspective analysis

As shown in Table 9 and Fig. 3, the primary energy consumption of GHP is 8.7% and 13.8% higher than that of EHP respectively in cooling and heating. This result is caused by higher COP of EHP compared with GHP. As the COP of EHP is more than twice as high as that of GHP, the primary energy consumption of EHP could be lower than that of GHP, even though there is much loss in the generation, transmission and distribution process.

Tables 10–12 show the annual primary energy costs of EHP and GHP system which are calculated based on the LNG price and Bunker C oil retail price in 2008. As the primary energy

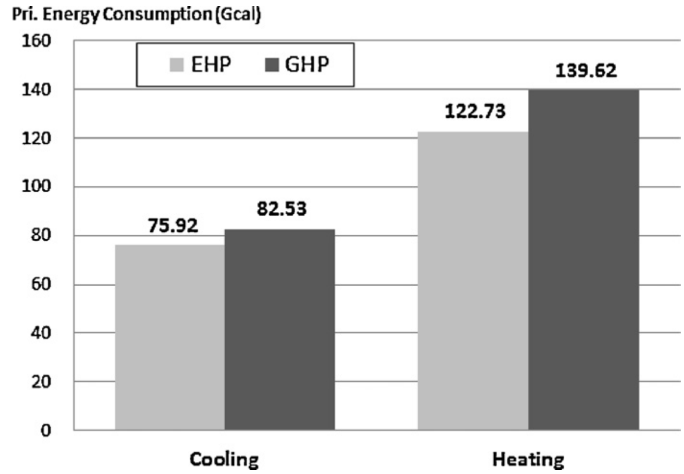


Fig. 3. Primary energy consumption of each system.

consumption of EHP is less than GHP, the primary energy cost of EHP is naturally less than GHP. Moreover, because EHP uses electricity generated by both Bunker C oil, cheaper fuel than LNG, and LNG, the gap between the primary energy cost of EHP and that of GHP is about 1% larger than that between the primary energy consumption of EHP and that of GHP.

4.2.2. Consumer perspective analysis

Table 13 shows the heating and cooling energy consumption from the final consumer perspective.

While EHP system uses electricity only, GHP system uses both electricity and natural gas by electrical equipments and gas engine, respectively. Table 14 shows the energy costs of heating and

Table 8
O&M costs of each system (kKRW/year).

	EHP	GHP
Space charge	186.00	93.00
Insurance	105.10	114.03
Repair cost	463.68	838.47
Total	754.78	1045.50

Table 9
Primary energy consumption of each system.

		Cooling		Heating	
		EHP	GHP	EHP	GHP
LNG	N m^3	5028.77	7522.36	8128.69	12,748.16
	Gcal	53.05	79.36	85.76	134.49
B–C	ℓ	2310.12	320.52	3734.16	518.10
	Gcal	22.87	3.17	36.97	5.13
Total	Gcal	75.92	82.53	122.73	139.62
	%	100.00	108.71	100.00	113.77

Table 10
Annual primary energy costs for cooling.

		EHP	GHP
LNG	kKRW	2663.44	3984.14
B–C	kKRW	1118.33	155.16
Total	kKRW	3781.76	4139.31
	%	100.00	109.45

Table 11
Annual primary energy costs for heating.

		EHP	GHP
LNG	kKRW	4305.28	6751.94
B–C	kKRW	1807.71	250.81
Total	kKRW	6112.99	7002.75
	%	100.00	114.56

Table 12
LCP of each system (kKRW/year).

	EHP	GHP
Primary energy supply cost	9894.75	11,142.05
%	100.00	112.61

Table 13
Final energy consumption of each system.

	Cooling		Heating	
	EHP	GHP	EHP	GHP
Electricity (kWh)	35, 758.77	4961.36	57, 801.85	8019.74
Gas (Nm^3)	–	6824.64	–	11,620.34

Table 14
Consumer energy costs of each system (kKRW).

	Cooling		Heating	
	EHP	GHP	EHP	GHP
Electricity	3370.62	467.66	5448.40	755.94
Gas	–	2244.49	–	6505.53
Total	3370.62	2712.15	5448.40	7261.47
%	100.00	80.46	100.00	133.28

Table 17
Unit incremental and avoided cost.

	Unit cost
Unit incremental generation construction cost (KRW/kW)	178,266
Unit avoided gas storage tank (KRW/ton)	93,985

cooling. The electricity rate is 2007 KRW 94.26/kWh, which is weighted average electricity rate for public and service use and educational use. For the natural gas used for GHP, gas rate of KRW 328.88/Nm^3 for cooling use and that of KRW 559.84/Nm^3 for heating use are applied in the calculation of the energy costs. The gas rate for cooling use is cheaper than that for heating thanks to the Korean government policy to promote the use of natural gas in summer season. [13]. As a result, in case of a cooling, GHP is superior to EHP. On the contrary, EHP is superior to GHP in case of heating, due to the higher gas rate in winter season than that in summer season. Consequently, considering the overall costs needed for both heating and cooling, the EHP is cheaper than that of GHP by about 13.1%.

Table 15 shows the total annual cost of the final consumer, which is calculated as the sum of the annual operation cost and the levelized initial investment cost. EHP is still superior to GHP by about 20.9%, similarly in the primary energy perspective. However, the gap can be reduced to about 15.4% if KRW 6 million per unit subsidy is provided by the gas cooling equipment installation subsidy program, which is currently implemented in Korea.

4.2.3. *Social cost perspective analysis*

Table 16 shows the analysis result of the social cost perspective. First, the derivation of the GHG emission cost is as follows. To calculate the environmental cost, unit GHG emission cost was assumed EURO 15/tCO_2 based on recent spot price fluctuation trend of EU-ETS[14]. Therefore, the unit GHG emission cost applied is KRW 22,500/tCO_2 applied exchange rate KRW 1500/EURO.

The incremental generation capacity construction cost and avoided LNG storage tank construction cost caused by newly installment of the cooling and heating system are calculated as follows. In case of unit incremental generation capacity construction cost, the research result of Korea Electrotechnology Research Institute is applied. And the result from the gas avoided cost study is applied to the calculation of the unit avoided LNG storage tank construction cost [15] (Table 17).

In Table 18, the incremental generation capacity costs and the avoided LNG storage cost caused by the installment of each system are computed based on the data in Table 17. Table 19 shows the result of the social cost perspective analysis. The analysis results are divided into the two cases: with and without consideration of the incremental and avoided cost. Firstly, in the case that does not consider the incremental and avoided cost, the levelized cost (LCS) of EHP system is still less than that of the GHP system. But, in the case considering the incremental and avoided cost, the result is reversed conspicuously. If EHP system is replaced by GHP system, additional power plant construction and gas storage tank construction can be avoided.

4.3. *Sensitivity analysis*

4.3.1. *Sensitivity of LCP by COP of GHP*

As shown in the previous analysis results, the EHP system is superior to the GHP system in every case except the case considering the incremental generation capacity construction cost and avoided LNG storage tank construction cost. In this regard, sensitivity analysis on factors, which are expected to cause the inferiority of GHP to EHP, is made. As GHP is superior to EHP from social cost perspective considering all the costs and the promotion of GHP use is desirable for stable electricity demand and supply balance and for constant natural gas demand over a year, it is meaningful work to make a sensitivity analysis of various factors and to find effective measures to promote the penetration of GHP. For this purpose, we performed a sensitivity analysis of COP of GHP and found the COP, which can make GHP competitive. The enhancement of COP could be achieved through technology development [16]. Figs. 4 and 5 show the points (break even point) at which GHP begins to have competitiveness in heating and cooling service respectively from the primary energy perspective. Here, the COP of EHP is assumed to be fixed. The analysis results show that the GHP system begins to have competitiveness when the COPs achieve the levels of 1.40

Table 15
LCC of each system (kKRW/year).

	EHP	GHP
Energy cost	8819.02	9973.62
O&M cost	754.78	1045.50
Total operation cost	9573.80	11,922.03
Levelized initial cost	9006.89	11,451.92
LCC	18,580.69	21,446.68
%	100.00	115.42

Table 16
Annual CO_2 emission cost of each system.

	EHP	GHP
LNG (tCO_2)	32.42	49.95
B–C (tCO_2)	19.20	2.66
Total (tCO_2)	51.62	52.61
Unit emission cost (KRW/tCO_2)	22,500	22,500
Emission cost (kKRW/year)	1161.45	1183.79

Table 18
Incremental and avoided costs by system.

	EHP	GHP
Coincident factor (%)	86.70	86.70
Incremental electricity demand (kW)	46.99	6.52
Incremental gas consumption (ton)	4.07	6.09
incremental generation capacity cost (kKRW/y)	8376.97	1162.27
Avoided LNG storage costs (kKRW/y)	−382.41	−572.03
Total (kKRW/y)	7994.56	590.24

Table 19
LCS of each system (kKRW).

		EHP	GHP
Primary energy supply cost		9894.75	11,142.05
O&M cost		754.78	1045.50
Levelized initial cost		9006.89	10,427.56
CO_2 emission cost		1161.45	1183.79
Incremental construction cost		7994.56	590.24
LCS	w/o construction cost	20,817.86	23,798.90
	w construction cost	28,812.43	24,389.14

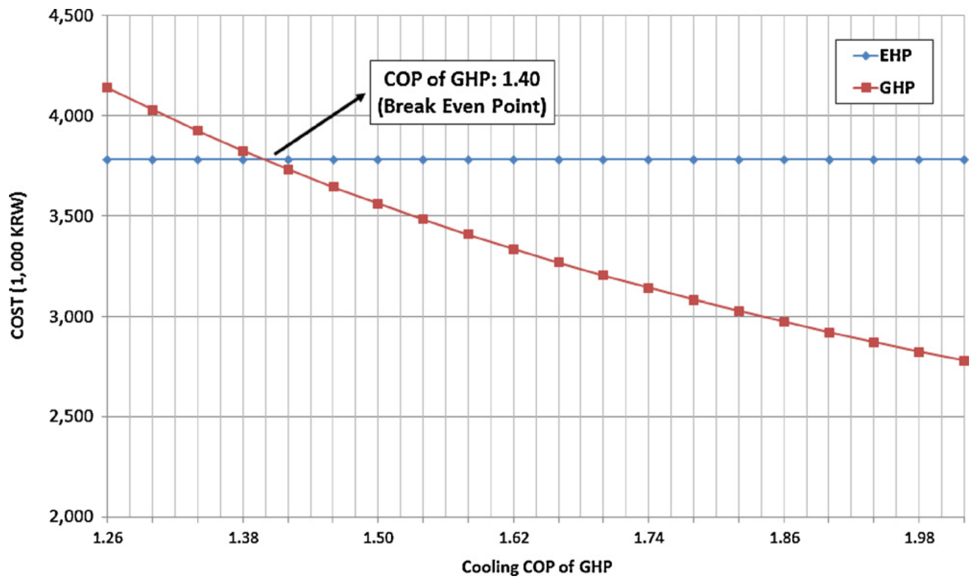


Fig. 4. Break even point of EHP&GHP for cooling COP.

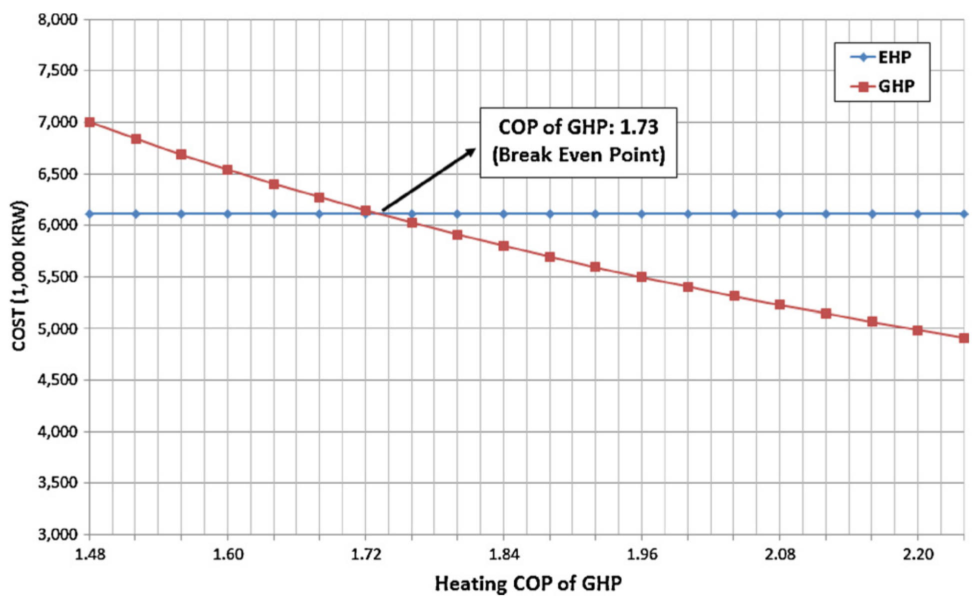


Fig. 5. Break even point of EHP&GHP for heating COP.

and 1.73 respectively for cooling and for heating from the primary energy perspective.

4.3.2. *Sensitivity of LCP by natural gas price*

This paper also conducted sensitivity analysis of primary energy costs of EHP and GHP following the changes in international natural gas price. For three international natural gas prices, 8$, 10$, and 12$/MMBtu, the primary energy costs of EHP and GHP are calculated. The international natural gas prices in USD/MMBtu are converted into KRW/Gcal in Table 20.

Table 21 and Fig. 6 show the primary energy costs following the international natural gas price changes.

The primary energy cost of GHP is less than that of EHP when international natural gas cost is about $6/MMBtu. However, as the international gas price increases, EHP becomes superior to GHP, and the gap between the costs of EHP and GHP is getting larger. This is natural in that the primary energy needed for GHP is almost from gas while that for EHP is from various fuels. Thus, it can be

Table 20
Natural gas price by scenario (KRW/Gcal).

Scenario	Natural gas price in KRW
$8/MMBtu	34,921
$10/MMBtu	43,652
$12/MMBtu	52,382

Table 21
LCP by natural gas price scenario (kKRW/year).

Scenario	EHP	GHP	GHP/EHP
$4/MMBtu	6131.97	5345.08	87.17%
$6/MMBtu	7343.84	7212.09	98.21%
$8/MMBtu	8555.70	9079.10	106.12%
$10/MMBtu	9767.56	10,946.11	112.07%
$12/MMBtu	10,979.43	12,813.12	116.70%

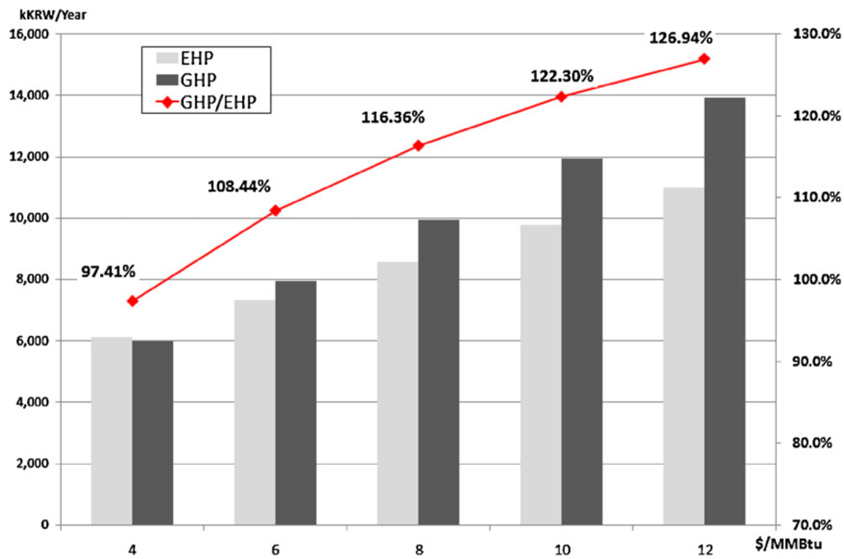


Fig. 6. LCP by natural gas price scenario.

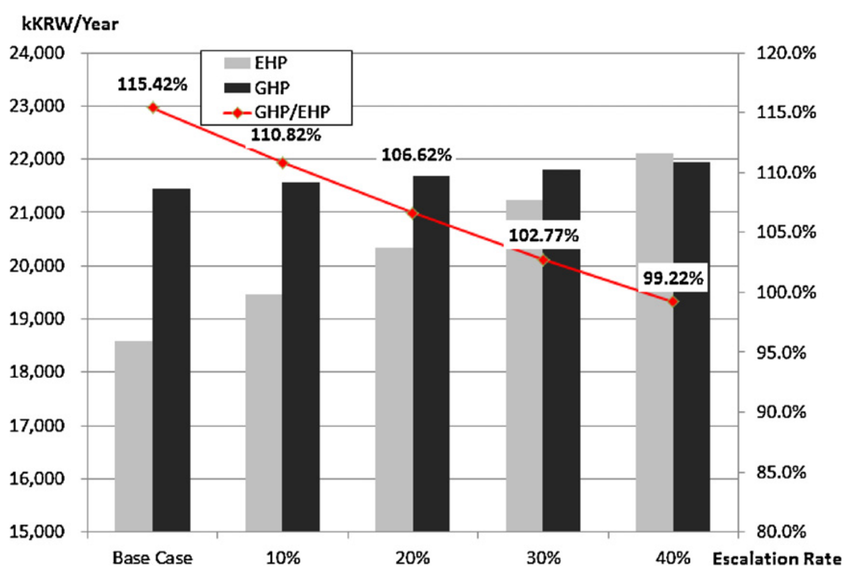


Fig. 7. LCC by electricity rate scenario.

said the cost of GHP is more sensitive to international natural gas price change.

4.3.3. *Sensitivity of LCC by electricity rate*

In this section, a sensitivity analysis of annual costs from final consumer perspective following the changes in electricity rates is made. Through this analysis, it is attempted to review the economic feasibility of each system when the current inflexible electricity rate system in Korea is changed into more flexible one [17].

The electricity rates scenario assumed in this sensitivity analysis includes (1) base rates applied in previous analysis, and (2) the rates increased by 10–40% from base rates. Electricity rates for each scenario are in Table 22.

As shown in Table 23 and Fig. 7, with increase in electricity rates, the gap between the annual cost of EHP and that of GHP gets smaller. Even though it is not much probable that electricity rates increase 40% in the near future, GHP could be superior to EHP when the electricity rates are raised as much.

Table 22
Electricity rate by scenario (KRW/kWh).

Scenario	Electricity rate
Base	94.26
Inc. by 10%	103.69
Inc. by 20%	113.11
Inc. by 30%	122.54
Inc. by 40%	131.96

Table 23
LCCs by electricity rate scenario (kKRW/year).

Scenario	EHP	GHP	GHP/EHP
Base	18,580.69	21,446.68	115.42%
Inc. by 10%	19,462.59	21,569.04	110.82%
Inc. by 20%	20,344.50	21,691.40	106.62%
Inc. by 30%	21,226.40	21,813.76	102.77%
Inc. by 40%	22,108.30	21,936.12	99.22%

5. Conclusions

This paper compares the costs of EHP and GHP from three perspectives, primary energy costs, final consumer's annual costs and social costs. From the primary energy and final consumer perspectives, EHP is superior to the GHP due to the EHP system's higher efficiency than GHP. Moreover, the convenience of EHP system makes it more preferable to final consumer. However, in the social cost perspective analysis considering the additional generation capacity construction costs and avoided LNG storage tank construction costs, GHP is more cost effective alternative.

In conclusion, while EHP might be beneficial for the reduction of primary energy import and preferable for final consumers, the larger penetration of GHP than current level is desirable in social or national point of view. These results could be useful for the future establishment of integrated demand side management policy in Korea.

As a result of sensitivity analysis, it is found that the changes in COPs, international natural gas price, and electricity rates could cause the changes in the comparative competitiveness between EHP and GHP. Although some of the break-even points that the GHP has competitiveness are a little unrealistic, if technology development such as an improvement of COP of GHP is continuously encouraged, fuel-switching EHP to the GHP could be an alternative for achieving both energy conservation and social cost minimization.

Acknowledgment

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